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Power Combiner

Field of the Invention

The current invention is directed to the class of power combiners comprising a plurality of input waveguides, hereafter referred to as feed waveguides summing input power into a single output waveguide, hereafter called a final waveguide. Because of symmetrical behavior in the present invention between input and output ports, the relevant field of the present invention also includes power splitters having a single input port dividing the power applied to this port into a plurality of output ports, dividing the power according to a desired ratio between these ports.

The present invention includes the class of power combiners which sum wave energy from a plurality of waveguides, each carrying traveling TE, TM, and HEmn mode electromagnetic waves. The traveling electromagnetic waves may be propagating either in a symmetric mode or in an asymmetric mode. The present power combiner has several

feed waveguides, a reflector for each feed waveguide, and a single final waveguide.

Background of the invention

In applications requiring the summing of a large number of output from klystrons launching TE01 mode waves into cylindrical waveguides, it has been necessary to first convert the waves to TE00 fundamental waves, and summing according to prior art techniques.

Examples of prior art power combiners are the class of circular power combiners such as U.S. Patent No. 5,446,426 by Wu et al, which describes a device accepting microwave power from the resonant cavity of a microwave oscillator, and summing into a circularly symmetric waveguide for delivery to an output port. U.S. Patent 4,175,257 by Smith et al describes another circular power combiner comprising radial input ports which furnish microwave power which is summed along a principal axis. U.S. Patent No. 4,684,874 by Oltman describes another radially symmetric power combiner/divider, and U.S. Patent No. 3,873,935 describes an elliptical combiner, whereby input energy is provided to one focus of the ellipse, and removed at the other focus. In all of these combiners, the output port is orthogonal to the input port, and the wave mode is TM, rather than TE.

U.S. Patent 4,677,393 by Sharma describes a power combiner/splitter for TE waves comprising an input port, a parabolic reflector, and a plurality of output ports.

For complete understanding of the present invention, a review of well-known traveling wave principles relevant to the prior art should be explained. References for traveling wave phenomenon are "Fields and Waves in Communication Electronics" by Ramo, Whinnery, and Van Duzer, Chapter 7 "Gyrotron output launchers and output tapers" by Möbius and Thumm in "Gyrotron Oscillators" by C.J. Edgcombe, and "Open Waveguides and Resonators" by L.A. Weinstein.

Circular waveguides support a variety of traveling wave types. Modes are formed by waves which propagate in a given phase with respect to each other. For a given free-space wavelength λ, a circular waveguide is said to be overmoded if the diameter of the waveguide is large compared to the wavelength of a wave traveling in it. An overmoded waveguide will support many simultaneous wave modes traveling concurrently. If the wave propagates axially down the waveguide, the wave is said to be a symmetric mode wave. If the wave travels helically down the waveguide, as shown in figure 16, the wave is said to be an asymmetric mode wave. In the case where two

identical asymmetrical helical waves are combined, the result is an asymmetric wave mode propagating axially. In the case of the present invention, helically propagating waves will be considered.

Transverse electric, transverse magnetic, or hybrid modes propagating in cylindrical waveguides have two integer indices. The first index is the azimuthal index m which corresponds to the number of variations in the azimuthal direction, and the second index is the radial index n that corresponds to the number of radial variations of the distribution of either the electric or magnetic field component. While the radial index n always has to be larger than zero, the azimuthal index m can be equal to zero. Due to their azimuthal symmetry, modes with m=0 are called symmetric modes whereas all other modes are called asymmetric. Asymmetric modes can be composed of a co- and counter- rotating mode with has the consequence that -as in the case of symmetric modes- the net power flow (real part of the poyntingvector) only occurs in the axial direction. However, if either the co- or counter- rotating mode is present there is a net energy flow in axial and azimuthal direction, hence we obtain a helical propagation. For the present invention helically propagating or symmetric modes are considered.

When using a ray-optical approach to the modes, a decomposition of the modes as plane waves with the limit of zero wavelength rays are obtained. In general, these are tangent to a caustic with a radius:

$$Rc = Rw\ (m/Xmn)$$

where:

Rc is the radius of the caustic

Rw is the radius of the waveguide

Xmn is the eigenvalue of the mode

This has the consequence that the geometrical rays have an azimuthal, radial, and axial coordinate. However, in the case of symmetric modes, the radius of the caustic becomes zero, and hence the rays representing symmetric modes only have a radial and an axial component. In the design of a reflector, the phase front of the rays tangent to a caustic is required. In an asymmetric mode, this phase front is the involute of the caustic. For a symmetric mode, the phase front reduces to a point representing the caustic with a radius = 0.

In a cylindrical waveguide, the radial component of the ray does not contribute to the net power flow. This however changes as soon as the waveguide has a port which causes a net power flow in the radial direction.

The phase front for an asymmetric mode wave is described by an involute in free space, a shape which is inwardly curled towards the center of the waveguide. The particular shape for the phase front for each wave mode unique, and is generally numerically calculated. The important aspect of the phase front is that it defines a particular surface, and this phase front will be used later for construction of certain structures of the invention.

Traveling waves can also be described in terms of the propagation velocity in a particular direction. Symmetric waves traveling down the axis of the waveguide have a purely axial component, and no perpendicular component. Asymmetric waves traveling helically down the axis of a waveguide have both an axial component, and a perpendicular component. There is a wave number $k = 2\pi/\lambda$, where λ is the wavelength of the traveling wave. In each axial (parallel) direction and transverse (perpendicular) direction of travel, the following wave numbers may be computed:

$$k_{perp} = X_{mn}/Rw$$

$$k_{par} = \mathrm{sqrt}\ \{k^2 - k_{perp}^2\}$$

In these calculations,

X_{mn} is the eigenvalue of the mode

m is the azimuthal index

Rw is the waveguide radius.

For asymmetric mode waves, the internally reflecting waves define a circle within the waveguide radius Rw known as a caustic. The radius of the caustic for an asymmetric mode wave is

$Rc=Rw(m/X_{mn})$

Where

Rc = radius of caustic

Rw = radius of waveguide

m = azimuthal index

n = radial index

X_{mn} is the eigenvalue of the mode

In cylindrical waveguides, the distance Lc represents the length of waveguide for which propagating TEmn, TMmn, or HEmn waves propagating in a cylindrical wavelength complete a 2π phase change. The formula for Lc is

$Lc=2\pi Rw\{k_{par}sqrt\{1-(m/X_{mn})^2\}\}/\{k_{perp}\cos^{-1}(m/X_{mn})\}$

where

Rw, m, n, X_{mn}, k_{perp}, k_{par} are as previously defined

Objects of the invention

A first object of the invention is the summation of a plurality of symmetric waves such as TE01, TE02, TE03, etc. from a plurality of feed waveguides into a single final waveguide.

A second object of the invention is the summation of a plurality of asymmetric waves with azimuthal index m > 0 such as TE11, TE12, TE21, etc. from a plurality of feed waveguides into a single final waveguide.

A third object of the invention is the summation of a plurality of either traveling symmetric or traveling assymetric waves, each traveling wave coupled into a feed waveguide, thereafter coupled to a feed waveguide launching port, thereafter to a reflector, and thereafter to a summing final waveguide.

A fourth object of the invention is the splitting of a plurality of either traveling symmetric or traveling asymmetric waves applied to a final waveguide, these traveling waves thereafter coupled to a reflector, and thereafter coupled to a plurality of feed waveguides.

Summary of the Invention

A power combiner has a plurality of feed waveguides, each feed waveguide having an input port and a launching port. The input port accepts either symmetric or

asymmetric traveling waves, and the launching port emits these traveling waves to a focusing reflector. Each launching port has its own focusing reflector. A plurality of feed waveguides and focusing reflectors is arranged about a central axis. A final waveguide is disposed on this central axis for the transport of combined wave energy reflecting of the reflectors. Each feed waveguide is energized with a source of traveling wave energy, and this traveling wave energy is directed to the reflectors by the launching port of the feed waveguide, combining in the final waveguide.

Brief Description of the Drawings

Figure 1 shows a single feed waveguide and a reflector for symmetric mode waves.

Figure 1a shows the detail of a feed waveguide when unfolded into a plane.

Figure 2 shows cross sectional views of figure 1

Figure 3 shows a power combiner which sums input power from three symmetric wave sources.

Figure 4 shows the cross sectional views of figure 3

Figure 5 shows a power combiner which combines input power from four symmetric wave sources.

Figure 6 shows the cross sectional views of figure 5.

Figure 7 shows the details of the reflector construction in a collapsed section view.

Figure 8 shows a collapsed section view of the reflector, feed waveguides, and final waveguide for the power combiner of figure 5.

Figure 9 shows a single feed waveguide, a reflector, and a final waveguide for asymmetric waves.

Figure 10 shows a feed waveguide for asymmetric wave sources, the feed waveguide shown unwound onto a planar surface for clarity.

Figure 11 shows a final waveguide for asymmetric wave summing, the final waveguide shown unwound onto a planar surface for clarity.

Figure 12 shows final waveguide of figure 11 unwound onto a planar surface, and with shaded areas showing the progressions of traveling wave energy

Figures 13a and 13b show different views of a power combiner for asymmetric mode input power which is summing asymmetric mode input power from 3 sources.

Figures 14a and 14b show a power combiner for asymmetric mode input power which is summing asymmetric mode input power from 4 sources.

Figure 15 shows wave propagation in a waveguide as the geometrical optical summing of a plurality of individual geometric optic waves into a helically traveling wave.

Figure 16 shows the helically traveling wave in a waveguide.

Figure 17 shows the collapsed section view of 4 feed waveguides, the final waveguide, and the reflectors.

Figure 18 shows the details of construction of a single reflector.

Figure 19 shows power summing in the final waveguide.

Detailed Description of the Invention

Figure 1 shows a feed waveguide 10 arranged about a feed waveguide axis 18, and figure 2 shows the cross sections of the related structures of figure 1. Typically, these feed waveguides are fed by high power klystrons in TE_{01} mode from a cylindrical waveguide. The feed guide 10 has a radius 13, an input port 15, and a launching port 12 centered on the feed waveguide axis 18. In one embodiment optimized for symmetric waves, the feed waveguide 10 has a cylindrical part L1 16 which is of a sufficient length to remove higher mode waves that may be present in the feed waveguide, a feed port 15 for receiving input power, and a launch port 12 for directing wave energy towards a

reflector 14. The first section of the feed waveguide is shown in section A-A of figure 2. Figure 1 shows a launch port section 12 which comprises a cylindrical section having the same diameter and waveguide axis 18 as the input section, and further has a length L_{launch} of the launch port which is optimally

$$L_{launch} = Lc/2$$

where

L_{launch} is the length of the feature 20 in figure 1

$Lc=2\pi Rf\{k_{par}sqrt\{1-(m/X_{mn})^2\}\}/\{k_{perp}\cos^{-1}(m/X_{mn})\}$. As described earlier, Lc represents the length of a waveguide section for which propagating TEmn, TMmn, or HEmn waves propagating in a cylindrical wavelength complete a 2π phase change.

Rf is the radius of the feed waveguide

k_{par} is the parallel, or axial wave number

m is the azimuthal index of the mode

X_{mn} is the eigenvalue of the mode

K_{perp} is the perpendicular wave number

For a symmetric mode wave, m=0, and so the equation for Lc simplifies to

$$Lc=4Rf\{k_{par}\}/\{k_{perp}\}$$

and therefore

$$L_{launch} = 2Rf\{k_{par}\}/\{k_{perp}\}$$

Figure 1a shows the feed waveguide 10 unfolded onto a planar surface with the features dimensioned for clarity.

Figure 2 shows the cross section B-B of the second section having an included angle α1 24 which is preferably 180 degrees. The angular extent of the reflector 14 may be greater or smaller than 180 degrees, depending on the location of the center of the reflector with respect to the feed waveguide axis 18, and the spatial requirements of the other reflectors. In general, the available included angle for each reflector will be 360/k degrees, where k is the number of feedguides present, as will be explained later with figure 8. In figure 2, focusing reflector 14 may comprise an elliptical surface having an included angle α2 26 determined by the included angle 64a and 64a' of figure 8, which will be 360/k degrees, where k is the number of feed waveguides present. The length L3 22, should be of sufficient length to enable reflection of most of the incident power from a launching port 12 into a final waveguide. The launching port 12 may be defined as the cylindrical section formed by sweeping a line of length L_{launch}, with a separation from the feed waveguide axis 18 equal to feed waveguide radius 13 about an included angle

α1 24. Focusing reflector 14 is disposed about feed waveguide axis 18, and has a length L3 sufficient to reflect waves leaving the feed waveguide 10 into the final waveguide.

Figure 3 shows a power combiner comprising three feed waveguides 30a, 30b, and 30c. Incoming sources of symmetric wave energy enter each of the three feed waveguides 30a, 30b, and 30c, which are arranged symmetrically about a power combiner central axis 36, also shown in section E-E of figure 4. The symmetric wave energy exits at the feed waveguide launching port, shown in section F-F of figure 4. Focusing reflectors 32a, 32b, and 32c act on energy exiting each of feed waveguides 30a, 30b, and 30c respectively. Each feed waveguide is arranged with its feed waveguide central axis parallel to the power combiner central axis 36. The focusing reflectors direct wave energy to final waveguide 34. Figure 4 shows the section details of the structures of figure 3. Section E-E shows the feed waveguides 30a, 30b, and 30c of figure 3. Each of the feed waveguides 30a, 30b, and 30c has an identical radius 38, shown only on waveguide 30a as 38a for clarity. Section F-F shows the launching ports of feed waveguides 30a, 30b, and 30c. Section G-G shows the arrangement of focusing reflectors 32a, 32b, and 32c, which

will be described in detail later. Section H-H shows the cylindrical sectional view of final waveguide 34, which has a radius 40, and is disposed about the central axis 36. In accordance with best mode shown in figure 4 section F-F, the launching ports are convex with respect to the power combiner central axis 36, while the reflectors 32a, 32b, 32c of section G-G are concave with respect to the power combiner central axis 36. In an alternate construction, each of the feed waveguides could be rotated 180 degrees about its own respective waveguide axis to produce launch ports which are concave when viewed in section F-F of figure 4, and each of the reflectors could be rotated 180 degrees about each feed waveguide central axis to produce reflectors which are convex with respect to the power combiner central axis 36. As is clear to one skilled in the art, this arrangement would produce a feed waveguide launching port which directs energy towards the central axis 36, and would be reflected by each reflector to the final waveguide 34. However, it is believed that the arrangement of figure 3 would produce the best power combiner. Also, while the feed waveguide radius 38 is shown as equal for each of the feed waveguides, it is possible for the power combiner to have unequal feed waveguide radii for each feed waveguide. While the feed

waveguides of figure 3 are shown distributed equally about the central axis 36 as is believed to be the best mode, it is also possible to arrange the feed waveguides with an unequal angular distribution. This angular distribution could be described in terms of the included angle formed between the planes which include each feed waveguide axis and the power combiner axis 36.

In the final waveguide 34, different wave modes may be present than were present in the feed waveguides 30, so the wave mode in the final waveguide will be described as TEpq, where p & q are the final waveguide mode numbers. For the final waveguide, the radius Rfinal and wave mode indices p and q should be chosen such that the brillouin angle for the mode in the final waveguide matches the brillouin angle for the mode in the feed waveguide. Since the radius Rfinal is generally larger than the radius of the individual feed waveguides, the mode indices will be higher as well. If the two feed waveguides carry TE_{01} mode, and it is desired to carry TE_{02} in the final guide, then R_{final} may be determined by

$$R_{final} = R_{feed}\ (X_{02}/X_{01}).$$

In general,

$$R_{final} = R_{feed}\ (X_{mn}/X_{pq})$$

where

R_{final} = radius of final waveguide

R_{feed} = radius of feed waveguide

X_{mn} = eigenvalue of mode in feed waveguide

X_{pq} = eigenvalue of mode in final waveguide

In addition to the above selection or Rfinal, the additional constraint Lfeedhelix = Lfinaldepth must be met. Since this criterion will generally not be met for a given feed waveguide mode and final waveguide mode, this is accomplished by utilizing the observation that the spectrum of eigenvalues of the various modes is dense. This constraint is met by making an appropriate selection between the available wave modes found in the feed waveguide and final waveguide, and the feed and final waveguide radii.

Figure 5 shows a power combiner with 4 feed waveguides 50a, 50b, 50c, and 50d. Symmetric mode wave energy enters each of the feed waveguides 50, and is directed to a launching port, as before. The wave energy leaving each launching port 50a, 50b, 50c, and 50d is sent to each reflector 52a, 52b, 52c, and 52d, and thereafter is reflected to final waveguide 54. Figure 6 shows the cross sectional views of the power combiner/splitter of figure 5. Section J-J shows the arrangement of feed guides 50a-50d,

including the launching ports of section K-K. Section L-L shows the reflectors 52a-52d, and section M-M shows the output guide 54.

Figure 7 shows the construction details for a single reflector, shown as reflector 52a of figure 5. The reference points of figure 7 are the final waveguide axis 56 and the feed waveguide axis 51a. Wave energy leaves the center of feed guide 51a and is directed to the center of final waveguide 54. These two points are used to construct the locus of points which define the reflector 52. By the geometric optics technique of ray tracing, the reflector 52 is formed by the locus of points forming an equidistant total path from a first focus 51a, to the reflector 52a, and to the center of the final waveguide 54. In figure 7, each exit path 60a, 60a', 60a'' is reflected from reflector 52a, and is directed to second focus 56 via reflected path 62a, 62a', and 62a'', respectively. The total path length 60a + 62a = 60a' + 62a' = 60a'' + 62a'', etc. Feed guide radius 38a and final guide radius 40 are also shown. The extent of reflector 52a is typically determined by the included angle about reflector reference plane 64a, formed by sweeping a plane which includes the main axis 56 about waveguide axis 51a. The solid angular extent of the reflector 50a is shown as the included angle from reflector

extent 64a′ to reflector extent 64a′′, which is typically symmetric about the reflector axis 64a. The angle from 64a′ to 64a′′ is determined by the number of reflectors present. In the case p=3 of 3 reflectors and 3 feed waveguides, the included angle of the reflector is 360/3=120 degrees. For the case p=4 of 4 reflectors and 4 feed waveguides, the included angle is 360/4=90 degrees. Any number of feedguides and reflectors may be accommodated in this manner. The reflector 52a comprises the locus of points providing equal path length from first focus to second focus, and is truncated by the included angle formed by 64a′ to 64a′′, which enables the reflectors for the other feed guides to utilize the remaining space.

Once the locus of points which defines the reflector 52a is determined as described above, it may be used to form the shape of the reflector along the waveguide axis 56. The formation of the reflector solid 52 from the locus of reflector points may be thought of as an extrusion of the locus of points along the power combiner axis 56 to form the reflectors 52a,52b,52c,52d of figure 5, or any of the other reflectors shown in previous figures. The axial extent of the reflector may be chosen based on minimum power loss when coupling energy from the launching ports to

the final waveguide. This axial extent is approximately the value Lc defined earlier.

Figure 8 shows the arrangement of feed guides, reflectors, and output guides for the case where k=4. Each feed guide 50a, 50b, 50c, 50d has a central axis, and reflectors 52a, 52b, 52c, and 52d respectively dispose wave energy to the central axis of final waveguide 54. Each reflector is symmetrically located about the connecting line between the two focal points, one at the central axis 56 and the other located at each feed guide center 51a, 51b, 51c, and 51d. These are also shown by the lines 64a, 64b 64c, and 64d. Typically, each feed waveguide and each reflector waveguide is coaxially arranged, although other arrangements, such as an angular offset between feed waveguides and reflectors could be accommodated. The result of the arrangement of feed waveguides, reflectors, and final waveguides in figure 8 is that input power from each feed waveguide 50a-d is reflected by reflector 52a-d, and is focused at the center of final waveguide 54.

Figure 9 shows the power summer/splitter for asymmetric mode waves. In the general case, a plurality of feed waveguides 70 would be used, but only one is shown in this figure for clarity. Asymmetric mode waves travel in a helical path, as will be described later. Feed waveguide

70 includes a feed waveguide axis 73, and a reference line 72 is shown to assist in understanding the actual shape of the feed guide. If feed guide 70 were unfolded about reference line 72, the shape would be as shown in figure 10. The circumference of feed guide 70 is equal to the number of wavelengths of the azimuthal mode, which is m wavelengths, or 2*pi*m radians in phase, and includes an exit surface of length 78 for the launching of waves towards the reflector 74 of figure 9. Feed guide central axis 73 is shown offset from main axis 71. Final waveguide 88 may be constructed on one of two different ways. For the special case where

$(\varphi_c)/2\pi = (1/\pi)\arc\cos(m/X_{mn})$ is an integer, where

m = azimuthal index

n = radial index

X_{mn} = the eigenvalue of the mode

the final waveguide may be a simple cylinder without the multicuts 88a, 88b, 88c, etc. For all other cases, the final waveguide includes a multi-cut input wave surfaces 88a, 88b, 88c, and 88d, as shown in figure 9.

The feed waveguide 70 of figure 9 includes a helical launch port which may be described by sweeping a line of length $L_{feedlaunch} = \theta * L_{feedhelix}/2\pi$ at the radius of the launch port from and parallel to said feed guide axis, where $0 \leq \theta$

≤ 2π and θ is the angle in radians about the feed waveguide axis 73 and $L_{feedhelix}$ is the depth of the helical cut 78. $L_{feedhelix}$ may be computed by

$$L_{feedhelix} = Lc$$

where

$$Lc = 2\pi R_{feed}\{k_{par}\mathrm{sqrt}\{1-(m/X_{mn})^2\}\}/\{k_{perp}\cos^{-1}(m/X_{mn})\}$$

k_{par} is the parallel, or axial wave number

R_{feed} is the radius of the feed waveguide

m is the azimuthal index of the mode

X_{mn} is the eigenvalue of the mode

K_{perp} is the perpendicular wave number

Sweeping the line $L_{feedlaunch}$ produces the helical launch ramp shown in figures 9 and 10.

As shown in figure 9, the multicuts 88a, 88b, 88c, 88d of the reflector port of the final waveguide may be constructed by sweeping a line of varying length $L_{finalmulticut}$ at the final waveguide radius from said central guide axis about an angle θ:

$L_{finalmulticut}$=

$$(Lc/k)*(\theta/(k*2*pi)) \text{ for } 0 \le \theta \le 2*pi/k$$

where

$$Lc = 2\pi R_{final}\{k_{par}\mathrm{sqrt}\{1-(p/X_{pq})^2\}\}/\{k_{perp}\cos^{-1}(p/X_{pq})\}$$

(Lc/k) is the multicut depth 77

k_{par} is the parallel, or axial wave number

R_{final} is the radius of the final waveguide

p is the azimuthal index of the mode

q is the radial index of the mode

X_{pq} is the eigenvalue of the mode

K_{perp} is the perpendicular wave number

k is the number of multicuts

The multicut of the final waveguide is formed by joining end-for-end k said surfaces of rotation to form a cylindrical solid, as shown in figure 9 for the case k=4.

Figure 9 also defines a drop and a ramp, which will be used later to show orientation of the helix in projection with respect to the helical cut. The drop may also be defined to be the location where $\theta = 0$ in the earlier definition of $L_{feedlaunch}$.

As was described earlier for the symmetric mode case, final waveguide 88 may have different wave modes present than were present in the feed waveguides 70, so the wave mode in the final waveguide will be described as TEpq, where p & q are the final waveguide mode numbers. For the final waveguide, the radius Rfinal and wave mode indices p and q should be chosen such that the brillouin angle for the mode in the final waveguide matches the brillouin angle

for the mode in the feed waveguide. Since the radius Rfinal is generally larger than the radius of the individual feed waveguides, the mode indices will be higher as well. If the two feed waveguides carry TE_{01} mode, and it is desired to carry TE_{02} in the final guide, then R_{final} may be determined by

$$R_{final} = R_{feed} (X_{02}/X_{01}).$$

In general,

$$R_{final} = R_{feed} (X_{mn}/X_{pq})$$

where

R_{final} = radius of final waveguide

R_{feed} = radius of feed waveguide

X_{mn} = eigenvalue of mode in feed waveguide

X_{pq} = eigenvalue of mode in final waveguide

In addition to the above selection or Rfinal, the additional constraint Lfeedhelix = Lfinaldepth must be met. Since this criterion will generally not be met for a given feed waveguide mode and final waveguide mode, this is accomplished by utilizing the observation that the spectrum of eigenvalues of the various modes is dense. By making an appropriate selection between the available wave modes found in the feed waveguide and final waveguide, and the feed and final waveguide radii, it is possible to meet this constraint.

Figure 11 shows the final waveguide 88 unfolded to a planar surface about reference line 89. In practice, helically propagating waves exit feed waveguide 70, are reflected by helical reflector 74, and are collected by multicut input final waveguide 88, entering at multicut surface 88a and other surfaces 88b, 88c, and 88d, as shown by the ray traces 80, 82 84, and 86. These rays enter at angle $\alpha 4$ 81. The value of angle $\alpha 4$ 81 is not the same as the brillouin angle but can be computed from

$$\tan \alpha 4 = \{k_{par} \mathrm{sqrt}\ \{1-\{p^2/X_{pq}^2\}\}\}/\{k_{perp} \cos^{-1}\{p/X_{pq}\}\}$$

where $p \neq 0$, and the other variables are as earlier defined. The final waveguide has final multicuts 88a,88b,88c,88d, of depth

$$L_{finaldepth}=L_c/k,$$

with parameters as defined earlier.

Figure 12 shows the path of input waves collected by each multicut collection surface, and includes an input surface for the multicut, each multicut surface corresponding to a surface collecting wave energy from each

reflector, and directing it to each multi-cut surface, as will be described later. The angular hatch patterns represent approximations of wave energy as it travels through the structure. For example, examining the multicut port 84, the series of identical hatch patterns correspond to the wave energy propagating through this path, which continues at the connection point at the top 4 bands to the right. Lc is shown graphically as the width of k bands (shown as k=4), and the Lfinaldepth 77 is Lc/k, as shown in figure 11. φ_c 83 is shown for reference, and will be described in detail later in figure 15. The circumference of final waveguide 88 is shown in figure 11 and 12 as L_{launch}.

Figure 13a shows for k=3 an asymmetric mode, 3 port power summing/dividing structure. Each feed guide 100a, 100b, and 100c has helically traveling waves which launch at the helical cut end 114 of each feed guide. The helical cut angle and feed guide diameter is designed as described in figure 10. The three reflectors 102a, 102b, and 102c capture and reflect wave energy leaving each feed guide 100a, 100b, and 100c respectively, and feed this energy into each multicut surface of the multicut final guide 116. Each multicut 118 is arranged to capture traveling wave energy from each reflector 102. Figure 13b shows a

different perspective view of figure 13a for clarity in viewing the multicut final waveguide, and it can be seen that wave energy leaving each reflector 102a, 102b, 102c is captured by each multicut face 118a, 118b, and 118c, respectively. The summed wave energy from each feed guide 100a-c thereafter travels down final guide 116.

Figure 14a shows the same power summer/divider for the case where k=4. As before, each feed guide 120a-d has a feed end and a helically cut output end described by the unwound detail of figure 10. The reflectors 122a-d capture and reflect traveling wave energy to each of the 4 multicuts 124a-d, respectively. Figure 14a and 14b show different views of the identical set of structures to enable clarity in viewing the helical cuts in the feed guide output waveguides 112, as well as the multicuts 124 of the final guide 126. The details of construction for the reflectors will be described later.

Figure 15 shows the geometric optic ray-tracing case for a single ray 150 entering the waveguide 140 having a wall radius 146, reflecting from the walls of waveguide 140, and eventually exiting the waveguide at point 148. Figure 15 shows this internal reflection in a projection view, where in addition to the internal reflection, the ray is also traveling down the longitudinal axis of the

waveguide. A plurality of such geometric optic rays traveling through the waveguide, with all such waves sharing the same launch angle and helical angle, would sum to produce traveling waves with helical propagation, with the mean radius of the traveling wave helix being located at a caustic radius Rc 144. The included angle between wall reflections is shown as Φ_c 143, where

$$\Phi_c/2 = 2 * \text{arc cos } (Rw/Rc) = 2 * \text{arc cos } (p/X_{pq}).$$

The overall effect of summing many such rays 150 is the helical wave propagation shown in figure 16, where the cylindrical waveguide 140 is shown having a waveguide radius Rc 146, and a caustic radius Rc 144, and the wave energy enters at entry locations 160a and 160b, travels helically along the paths shown, and exits at egress locations 160a' and 160b'. The waves maintain their caustic radius Rc 144, a characteristic of the launch angle at entry point 160a and velocity of propagation in the medium carrying the wave energy, which is typically air.

Figure 17 shows the construction details for the reflectors of asymmetric combiners of figures 9, 13 and 14. The symmetric mode reflector of figure 7 was formed using a locus of points which reflect wave energy from a first focus 51a to a second focus 56. In the construction of reflector 210a of figure 17, feed guide 212a has a caustic

Rc(feed) 218a as was described in figures 15 and 16. Waves traveling in the feed waveguide 212a have a constant phase front 240, shown as an involute which starts at point 242 and curls outward to a point 252 on the waveguide wall. Similarly, final waveguide 200 has a caustic 202 with Rc(final) 204, and waves traveling in the final waveguide have a phase front 250, shown as an involute starting at point 248'' and ending at point 242'''. The feed waveguide phase front 240 and final waveguide phase front 250 are specific to the mode of wave traveling in the respective waveguide, and are shown in figure 17 only to clarify construction details of the reflectors 210a. In ray tracing construction of the reflectors, the feed guide phase front 240 and final guide phase front 250 are perpendicular to the feed guide ray paths 242, 244, 246, and 248. When the reflector is formed to create equal optical path lengths from the phase front of the wave in the feed guide to the phase front of the wave in the final guide, maximal power summing is achieved. The reflector is formed by a locus of points which satisfy the following criteria for each locus point:

1) a first line segment starts at a given reflector locus point, passes tangent to the feed waveguide caustic Rc(feed), and terminates at the phase front of the feed

waveguide, and a second line segment which starts at the same given reflector locus point, passes tangent to the final waveguide caustic Rc(final), and terminates on the phase front of the final waveguide.

2) the path length of the first line segment added to the second line segment is a constant. This constraint makes the electrical distance from the a point on the feed waveguide phase front to the same phase point on the final waveguide phase front equal for all such phase front points, thereby ensuring constructive addition of the wave in the final waveguide.

3) At each locus point, an intersection point is defined by the intersection of the locus point of the reflector and a line which is tangent to the reflector curve at the locus point, and a perpendicular line which is perpendicular to the tangent line at the locus point, the perpendicular line bisecting the angle formed by the first line segment and the second line segment. This constraint ensures the reflector surface at the given locus point will act to reflect energy from the feed waveguide phase front to the appropriate point on the final waveguide phase front. Using this metric, the construction of the reflector is formed by the locus of points shown on figure 17. Reflector 210a is illustrated for simplicity by 4

points which are used as examples to show how these constraints are used to construct the reflector. Phase front 240 and caustic 214a Rc(feed) 218a of the feed waveguide and phase front 250 and caustic 202 Rc(final) 204 of the final guide are known from the characteristics of the desired input and output wave mode patterns. A first line segment starts at reflector locus point 242', passes tangent to the feed caustic 214a, and terminates on the feed phase front point 242. A second line segment starts at reflector locus point 242', passes tangent to Rc(final) 242'', and terminates at final waveguide phase front 242'''. Similarly, for given reflector locus points 244', 246', 248', there are respective first segments formed by lines which start at the reflector locus points 244', 246', and 248' respectively, pass tangent to the feed caustic Rc(feed) 214a, and terminate on the feed guide phase front 240 on points 244, 246, and 248. Respective second lines are formed by lines which start at respective locus points 244', 246', 248', pass tangent to the final waveguide caustic Rc(final) 202 on points 244', 246', 248', and terminate on the final waveguide phase front 250 on points 244'', 246'', 248'' respectively. At each given point, the reflector surface 210a has a tangent line which includes the given point, and a line perpendicular to this

tangent line which includes the given point on the reflector. The angle formed by the first and second line which includes the given reflector point is bisected by the perpendicular line, as is clear to one skilled in the art of reflectors and ray tracing. Thus, the entire reflector surface 210 is formed by the locus of points which meet the constraints described earlier: for each given reflector locus point, the sum of the first and second line segment lengths is equal, and at the given locus point of the reflector, a line perpendicular to the reflector surface at the given locus point bisects the angle formed by the first and second line at each given point. The locus of points which meet these criteria form the reflector surface.

Generalizing to the earlier symmetric mode case, we can further say that the reflectors follow the same constraint, where the feed and final guides for the symmetric case have a feed caustic Rc(feed) and a final caustic Rc(final) equal to 0. This simplification produces the reflectors earlier shown in figure 7 and 8. Figure 17 shows the projection view looking through the input side of the feed waveguides, through the reflector 210a, and finally through the final waveguide. In this view, the additional detail of the location and orientation of the

helical ramp of the feed guide and the multicut ramps of the final waveguide are shown. Point 215 is shown as the tip of the helical feed waveguide, showing the "ramp" side and the "drop" side, and points 221 and 223 indicate the relative locations of the tips of two multicuts, also showing the "ramp" and "drop" side, corresponding to the features of the multicut. The points 215, 221, and 223 are shown only to aid in the understanding of the relationship between the angular orientations of the ramps on each of the structures, and may be in different places than shown in figure 17. In practice, the angular positions of these points is determined by maximizing power transfer from the feed waveguides, through the reflectors, and to the final guide.

Figure 18 shows the collapsed section view for all reflectors and feed guides, for the case where p=4.

Figure 19 shows power summing in the final waveguide, for the case where p=4. Wave energy enters each multicut 124a, 124b, 124c, 124d from each reflector 120a, 120b, 120c, 120d as in figure 14, and these sum respectively into the traveling wave groups shown entering as 168a, 168b, 168c, and 168d, and exiting as 170a, 170b, 170c, and 170d.